RADIATION DOSE ASSESSMENT IN TORSO PHANTOM FROM SPECT-CT IMAGING

SITI FAIRUS BINTI ABDUL RAHMAN

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RADIATION DOSE ASSESSMENT IN TORSO PHANTOM FROM SPECT-CT IMAGING

by

SITI FAIRUS BINTI ABDUL RAHMAN

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DECLARATION

I certify that this thesis does not incorporate without acknowledgement any material previously submitted for a master, degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text. This is to certify that the dissertation entitled **"Radiation Dose Assessment in Torso Phantom from SPECT-CT Imaging"** is the bona fide record of research work done by Siti Fairus Binti Abdul Rahman, Matric Number P-IPM0053/15 during the period of February 2015 until January 2016. This dissertation is submitted in partial fulfilment for the degree of Master of Science (Medical Research). Research work and collection of data belong to Universiti Sains Malaysia.

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Siti Fairus Binti Abdul Rahman
Master of Science (Medical Research),
Advanced Medical and Dental Institute,
Universiti Sains Malaysia,
13200, Kepala Batas,
Pulau Pinang.
Date :

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LIST OF ABBREVIATIONS

^{99m}Tc	^{99m}Technetium
Al_20_3	Aluminium Oxide
AMDI	Advanced Medical and Dental Institute
ALI	Annual Limit of Intake
CT	Computed Tomography
CTC	Clinical Trial Center
EIR	Environmental Impact Result
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IEC	International Electrotechnical Committee
LEHR	Low Energy High Resolution
LLD	Lower Limit of Detection
$^{99}Mo/^{99m}Tc$	^{99}Molydenum/^{99m}Technetium
MRI	Magnetic Resonance Imaging
OSL	Optically Stimulated Luminescence
PMT	Photomultiplier tube
SPECT	Single Photon Emission Computed Tomography
SPECT-CT	Single Photon Emission Computed Tomography-Computed Tomography
SNM	The Society of Nuclear Medicine
TL	Thermoluminescence
TLD	Thermoluminescence Dosimeter

LIST OF SYMBOLS

%	percentage
^{o}C	Degree Celcius
μR	microRoentgen
μSv	microSievert
cGy	centiGray
cm	centimeter
cpm	count per minute
h	hour
keV	kilo electron volt
kV	KiloVolt
m	meter
mA	milliAmpere
mCi	milliCurie
MeV	Mega electron volt
mGy	milligray
mm	millimetre
mRad	millirad
nC	nanoColoumb
rad	radiation absorbed dose

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Radiation Dose Assessment in Torso Phantom from SPECT-CT Imaging

ABSTRACT

Single Photon Emission Computed Tomography-Computed Tomography (SPECT-CT) systems are one of the latest technologies that have been used regularly in nuclear medicine imaging because of their ability to provide precise localisation of the anatomical images and physiological data from nuclear medicine studies. However, the exposure to radiation especially x-rays pose risk of inducing cancer in patients. Therefore, quantifying the radiation dose from SPECT-CT imaging was the main aim of this study in order to ensure that patients are exposed to minimal amount radiation. Torso phantom was used as a model to measure the radiation dose. ^{99m}Technetium was used as the tracer for SPECT where 2 mCi of ^{99m}Technetium was injected into the liver region of the torso phantom and low dose CT protocol was used for CT imaging. The measurement of radiation dose was repeated for three times using Thermoluminescence Dosimeters (TLDs) as the detector. The TLD readings were measured and converted to dose value. Prior to the usage, the TLDs were subjected to annealing, calibration and also sensitivity testing in order to select the most suitable TLDs for radiation measurement. The results showed that the sensitivity factors of all the chosen TLDs were from 0.800 to 1.250 which falls within the standard acceptable limit. Furthermore, the temperature, relative humidity and also background radiation that were monitored pre and post imaging falls within the acceptable range specified by International Atomic Energy Agency (IAEA). The mean effective dose obtained for CT imaging was 0.025 mSv, the dose from SPECT was 3.6×10^{-4} mSv and dose from the hybrid system SPECT/CT was 0.028 mSv. Thus, the radiation dose for SPECT-CT imaging was higher compared to the doses measured from individual SPECT and CT imaging. This

because the dose from SPECT-CT imaging is the summation doses from gamma rays emitted by ^{99m}Technetium injected into the phantom and also x-ray from CT machine. However, since the ^{99m}Technetium is a radioisotope that emits very low dose of gamma rays and low dose CT protocol was used in this study, the amount radiation exposed to patient was still relatively low. These signify that patient are exposed to safe amount radiation and thus, minimise the potential side effects that arises from radiation exposure.

Penilaian Dos Sinaran dalam Fantom Torso Menggunakan Pengimejan SPECT-CT

ABSTRAK

Sistem SPECT-CT adalah salah satu teknologi terkini yang kerap digunakan dalam pengimejan perubatan nuklear kerana keupayaan SPECT-CT untuk menunjukkan lokasi yang tepat untuk imej anatomi dan data fisiologi daripada kajian perubatan nuklear. Walau bagaimanapun, pendedahan kepada sinaran terutama sinar-x boleh mengakibatkan risiko yang mendorong kepada kanser dalam kalangan pesakit. Oleh itu, mengukur dos sinaran daripada SPECT-CT adalah motif utama kajian ini untuk memastikan bahawa pesakit terdedah kepada jumlah sinaran yang minimum. Fantom torso telah digunakan sebagai model untuk mengukur dos sinaran. ^{99m}Technetium ialah radioisotop yang telah digunakan untuk SPECT di mana sebanyak 2 mCi di suntik pada bahagian hati dan protokol dos rendah CT telah digunakan untuk pengimejan CT. Ukuran dos sinaran diulang sebanyak tiga kali menggunakan dosimeter termopendarcahaya (TLD) sebagai alat pengukur. Bacaan TLD diukur dan ditukar kepada nilai dos. Sebelum digunakan untuk mengukur dos, TLD akan melalui proses penyepuhlindapan, penentukuran dan juga ujian sensitiviti untuk memilih TLD yang paling sesuai dipilih untuk pengukuran sinaran. Hasil kajian menunjukkan bahawa faktor-faktor sensitiviti untuk semua TLD terpilih adalah antara 0.8-1.25 yang berada dalam lingkungan had piawai yang tetapkan. Selain itu, suhu, kelembapan dan sinaran latar belakang yang dipantau sebelum dan selepas pengimejan berada dalam lingkungan had piawai yang tentukan oleh Agensi Tenaga Atom Antarabangsa (IAEA). Selain itu, purata dos effektif yang diperoleh untuk pengimejan CT adalah 0.025 mSv purata dos radiasi dari SPECT adalah 3.6×10^{-4} mSv dan purata dos dari sistem SPECT-CT adalah

0.028 mSv. Oleh itu, dos sinaran untuk pengimejan SPECT-CT adalah lebih tinggi berbanding dengan dos sinaran untuk SPECT dan CT sahaja. Ini kerana dos sinaran SPECT-CT adalah hasil jumlah sinar gamma yang dipancarkan oleh ^{99m}Technetium yang di suntik ke dalam fantom dan juga sinar-x dari pengimejan CT. Oleh kerana ^{99m}Technetium adalah radioisotop yang mengeluarkan sinaran gamma dalam kuantiti yang sangat rendah dan protokol dos rendah CT digunakan dalam kajian ini, jumlah sinaran yang terdedah kepada pesakit masih berada dalam lingkungan yang agak rendah. Ini menandakan pesakit terdedah kepada jumlah sinaran yang selamat dan ini mengurangkan kesan-kesan sampingan yang berpotensi untuk timbul daripada pendedahan sinaran.

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Medical imaging that provides detailed pictures of the status of our body organs and tissues at the molecular and cellular level is called molecular imaging. Molecular imaging techniques enable the body functions and also biological functions to be visualised. One of the fields of molecular imaging includes nuclear medicine. In nuclear medicine, radioactive materials are used for disease diagnosis and treatment. Specialised detectors are used to detect the radioactive materials in nuclear medicine imaging to produce a very specific and precise image of the body areas that are being visualised. Furthermore, nuclear medicine has also been used for the treatment of cancer and also several other diseases (Society of Nuclear Medicine and Molecular Imaging, 2014).

There are approximately 100 nuclear medicine imaging procedures available using various single photon emission isotopes and positron emission isotopes till date. There are several important characteristics required for an ideal radioisotopes used for nuclear medicine imaging that are efficient accumulation and retention in the target organ, rapid clearance from tissue and blood, no accumulation in non-target tissue, no side effects, low cost, easy to be prepared and also have high specificity. The most commonly used radioisotopes in nuclear medicine include ^{67}Gallium, ^{131}Iodine, ^{99m}Technetium, ^{11}Carbon, ^{82}Rubidium, ^{18}Fluorine and ^{201}Thalium (McGoron A.J, 2002).

Single Photon Emission Computed Tomography-Computed Tomography (SPECT-CT) systems are one of the latest technologies that have been used regularly in nuclear medicine imaging because of their ability to provide precise localisation of the anatomical images and physiological data from nuclear medicine studies. SPECT-CT also provides accurate and precise attenuation correction of the nuclear medicine imaging data. The integration of SPECT and CT into a single imaging unit permits the acquisition of SPECT and CT data sequentially in a single patient study with the patient in a fixed position. CT data can be used to correct for tissue attenuation in the SPECT scans on a slice by slice basis. Furthermore, the CT data are usually blurred for the purpose of matching with SPECT data because CT data are acquired in a higher resolution matrix compared to the SPECT data. One of the advantages in using CT data for attenuation correction is CT scan provides a high photon flux that significantly reduces the statistical noise associated with correction. In addition, the duration of imaging is also significantly reduced due to fast acquisition speed of CT scanners (Patton J.A. and Turkington T.G., 2008).

The estimation of radiation dose to organs and tissues of the body are crucial whenever any radioisotopes are administered to patients regardless for diagnosis or therapeutic purposes. This is mainly because an analysis of risks and benefits is needed to justify and optimise the procedures involve any usage of ionising radiation. Estimation of radiation dose is usually done through mathematical calculations based on a standardised formula. Moreover, radiation dose estimates are performed using theoretical models since it is no feasible to make direct measurements of the radiation doses received. The characterisation of radiation doses received by various tissues in the body would require the utilisation of both standardised models of human body and radioisotopes behaviour. Broad generalisation of doses to the nuclear medicine population for a particular patient group is usually acceptable in diagnostic applications (Stabin M.G., 2008).

The radiation dose calculations for radioisotopes used in diagnostic are typically carried out using mathematical human modelling known as phantom. Phantoms are primarily invented to resemble human body that comprises of all the internal and external anatomy where radiation risks are concerned. Since phantoms are adequately close to real human anatomy including organs position, volume and also shape, the phantoms and its development methodology are proven to be useful in radiation dose determination not only for diagnostic purpose but also for radiation therapy (Lee C.S. and Lee J.K., 2006).

1.2 Background of the Problem

Over the past years, there have been two major types of risk identified with the administration of radioisotopes patient either for diagnosis or therapeutic reasons. One of them is the risk to the patient itself whereas the other type of risk is related to critical groups that are possibly exposed to the patient. The radiation emitted from the radioactivity that was retained by the patient presents a risk to those who are exposed to them (Helal N., 2012). Although CT is an important tool in medicine, it being a high radiation dose instrument has the potential like other sources of ionising radiation to cause cancer. Even though these risks are difficult to be accurately measured and determined, however, it has been shown that the risk of developing cancer is slightly increased if you have been exposed to additional ionising radiation above background levels.

National Council on Radiation Protection and Measurements has reported that the exposure to medical radiation has experienced significant rise for more than six fold from 1980's till 2006. Moreover, the risks are not the similar for all people where for instance, females are slightly more sensitive to the effects of ionising radiation compared with males (National Cancer Institute, 2013). Therefore, the need to determine the benefit to risk ratio where the risk is minimise and the benefits maximise in the usage of radiation for diagnostic purpose in nuclear medicine techniques has become very crucial.

Besides that, since usually nuclear medicine diagnostic examinations are associated with low radiation doses, thus one may question the need for thorough dosimetry investigation and optimising as long as image quality is sufficient. This is because, for the individual, the benefit from the examination is probably worth the small excess risk of inducing cancer, but looking at a population this excess risk may turn into significant numbers and become a burden for society (Hasson E., 2012). Thus, the estimation of radiation dosage is very important because this allows for risk comparisons across different radioisotopes and simplifies dose estimations in case of misadministration.

1.3 Problem Statement

In recent times, much effort has been invested to minimise the potential side effects of radiation either emitted from radioisotopes or radioactivity. Recently, various dosimeter technology and software have been developed to quantify and calculate the amount of radiation dose that will be subjected to patient either in diagnostic or therapeutic procedures. In this study, a well establish dosimetry technology known as Thermoluminescence (TL) dosimeter will be used to determine the radiation dose of ^{99m}Technetium and x-rays in SPECT-CT imaging using a phantom. The proposed dosimeter technology may allow a more accurate, effective and also environmental stable method to obtain the radiation dose of radioisotopes and also x-rays.

1.4 Research Objectives

The general objective of this study is to investigate the radiation dose for torso section in SPECT-CT imaging.

The specific objectives of this study are as follows:

i. To evaluate the characteristics of TLDs to obtain accurate and reliable results.
ii. To measure and to compare the radiation dosage in CT, SPECT, and hybrid SPECT-CT imaging using torso phantom.

1.5 Research Questions

i. How do we evaluate the characteristics of TLDs for obtaining accurate and reliable results?
ii. What is the measurement of radiation dose in CT, SPECT and hybrid SPECT-CT imaging and the comparisons of doses between the three imaging procedures are made?

1.6 Research Hypotheses

i. All the characteristics of TLDs are within the good operating condition that allows the better performance of the TLDs.
ii. The radiation dose of hybrid SPECT-CT imaging is higher compared to the radiation dose of individual CT and SPECT imaging.

1.7 Scope of the Study

This study focuses on the application of the one of the latest innovation of Thermoluminescence Dosimeters (TLDs) known as HARSHAW TLD100 to determine the radiation dosage of hybrid SPECT-CT, CT and also SPECT imaging using torso phantom. The HARSHAW TLD100 provides a single point radiation measurement. The TLD100 dosimeters was embedded on torso phantom to obtain specific individual radiation dosage for SPECT, CT and hybrid SPECT-CT imaging and the differences in the dosage will be compared and analysed to achieve a more accurate and reliable results. The TLDs sensitivity will be also tested prior to usage to measure the radiation to ensure the TLDs are in good condition to measure the radiation.

1.8 Significance of the Study

The use of SPECT-CT imaging procedure either for diagnostic or therapeutic purposes is becoming more intensive in recent years. However, hybrid SPECT-CT imaging is still considered a new technology in Malaysia. Most of hospitals and institution in Malaysia are equipped with the individual SPECT or CT machines. Therefore, till date very limited study related to the hybrid SPECT-CT system is performed in Malaysia.

Most of the studies so far emphasised on the technical aspects of the hybrid SPECT-CT machine and also the imaging procedures. There is still not much research that focus in the quantitative assessment of radiation from hybrid SPECT-CT imaging has been carried out especially in Malaysia. The risk upon the exposure to any form radiations either from radioisotopes or x-ray has been the major concern. This is because many studies has indicated that radiation especially x-ray has the ability to induce cancer in patients that undergo CT procedure for diagnostic purpose (Kron T., 1999). Thus, is very important to optimise the SPECT and CT protocols to ensure that patients are exposure to the lowest dose that is sufficient only for imaging so that that the risk can be minimised as low as possible.

Apart from that, there is very little published study that demonstrates the comparison of radiation dosage between SPECT, CT and also hybrid SPECT-CT. Therefore, this study also aims to highlight the differences in the radiation doses of hybrid SPECT-CT imaging with SPECT and CT imaging.

1.9 Research Framework

Physical Inspection of SPECT-CT Examination room

- ✓ Background radiation
- ✓ Temperature and humidity
- ✓ Calibration of dose calibrator

↓

TLD calibration and sensitivity testing

↓

Preparation of SPECT-CT Machine prior to imaging

- ✓ Calculation of amount of ^{99m}Tc to be injected into each organ
- ✓ Injection of ^{99m}Tc into each organs
- ✓ Embedding the TLDs on the phantom

↓

SPECT-CT Imaging

↓

Radiation Dose Measurement

- ✓ Radiation doses were measured from the imaging modalities
  1) Dose from hybrid SPECT-CT system
  2) Dose of SPECT scanner only
  3) Dose of CT scanner only

CHAPTER 2

LITERATURE REVIEW

2.1 Nuclear Medicine

Nuclear medicine is a branch of medical specialty that uses small amounts of radioisotopes as tracers for the diagnosis of diseases. Substances that can be attracted to special organs bones or tissues are referred as tracers. These tracers tend to emit characteristics radiation after being injected into the body where special electronic devices like gamma camera will detect the emissions and displays them into images. The displayed images provide information pertaining the anatomy and functions of the organs that are being imaged. The nuclear medicine techniques have extreme sensitivity and specificity for disease diagnosis compared to other diagnosis tests due to their ability to detect abnormalities during early stage of disease progression (Helal N., 2012).

There are various different kinds of diseases that can be diagnosed by nuclear medicine. Nuclear medicine is usually used for the detection of abnormal lesions deep in the body without the need of any kind of surgery. Besides that, nuclear medicine procedures can also be used confirm whether the organ functions are normal. For instance, nuclear medicine techniques can determine if our heart is pumping blood adequately to all organs. Furthermore, the smallest bone fracture can also be determined through nuclear medicine procedures. In terms of cancer, nuclear medicine can be applied to trace the cancer itself and also determine if they are responding well to the treatment. In addition, nuclear medicine is also use in disease treatment like treatment of hyperthyroidism by the usage of radioactive Iodine (The Society of Nuclear Medicine (SNM), 2004).

Nuclear medicine actually detects the radiation that originates from the patient's body. However, in techniques like x-ray, MRI and Ultrasound, the patients are exposed to the radiation from outside of their body using machines that send radiation through the body. Therefore, nuclear medicine procedures determine the cause of a medical problem through the basis of organ functions compared to other techniques that merely determine a disease based on the anatomy of organs (The Society of Nuclear Medicine (SNM), 2004).

2.2 Radioisotopes

Radioisotopes refer to the unstable atoms of a chemical element that are artificially produced. Radioisotopes usually have different number of neutrons but the same number of protons and the same chemical properties. Radioisotopes existence is measured depending on the time they take for half of the isotope to disappear which is also known as 'half-life'. A radioisotope is formed by bombarding a stable isotope with fast neutrons that are produced in a nuclear reactor or a particle accelerator and then it is transmuted into an unstable isotope of the same element. ^{131}Iodine was the first radioisotope that was used for as tracer. ^{131}Iodine was utilised for the diagnosis and also treatment of thyroid disease (Environmental Impact Result (EIR), 2008).

Over the years, it is seen that beta and gamma radiation from almost one hundred radioisotopes are used in diagnosis, therapy or for investigation purpose in nuclear medicine. Many studies have been reporting the successfulness of gamma emission imaging to nearly all organs of our body like brain, bone, kidney, lung, heart, neuroreceptors. Gamma emission imaging has also been effective at the sites of inflammation, arteriosclerosis, thrombosis and also cancer. Nuclear medicine imaging has resulted into a non-invasive pharmacokinetics modelling applications due to its molecular nature (McGoron A.J., 2002).

2.2.1 ^{99m}Technetium

In nuclear medicine imaging, ^{99m}Technetium is the most widely used radioisotopes, employed to nearly 80 % of all nuclear medicine procedures because of its virtually ideal physical characteristics for scintigraphic applications. The first artificially produced element was Technetium. Technetium was produced from the parent species known as ^{98}Molybdenum by bombarding with neutrons. ^{99}Molybdenum captures a neutron and becomes ^{99}Molybdenum. ^{99}Technetium was formed through the beta decay of ^{99}Molybdenum which has a half-life of 65.94 hours. ^{99m}Technetium is a metastable isotope of Technetium. ^{99m}Technetium has an excited nucleus and for the nucleus to enter a more stable state, it has to liberate out the excess energy which can be achieved by emitting a gamma ray (McGoron A.J., 2002).

^{99m}Technetium has a half-life of six hours which is long enough to examine metabolic processes yet short enough to minimise the radiation dose to the patient. ^{99m}Technetium decays by a process called isomeric transition which emits gamma rays and low energy electrons. The radiation dose to the patient is low since there is no high energy beta emission. The low energy gamma rays it emits easily escape the human body and are accurately detected by a gamma camera. ^{99m}Technetium can form tracers by being incorporated into a range of biologically-active substances to ensure that it concentrates in the tissue or organ of interest due to its versatile chemistry. ^{99m}Technetium is used for the imaging of various organs including skeletal, heart, brain, thyroid, lungs, liver, salivary and lachrymal gland (Eisenbud M. and Gessil T., 1997).

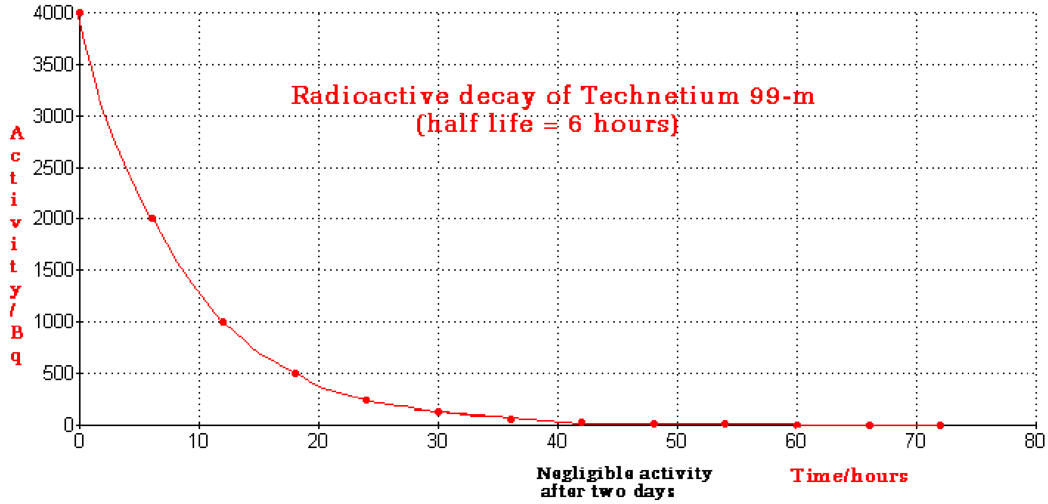

Figure 2.1 Graph demonstrating the radioactive decay of ^{99m}Technetium

The first ^{99}Mo/^{99m}Tc generator for clinical purpose was developed in the year of 1965. This has made ^{99m}Technetium more readily available for clinical research and also lead to generation of first labelled compound which imparted a great impact in nuclear medicine field. Over the years, the use of ^{99m}Technetium radiopharmaceutical in nuclear medicine has rapidly increased to more than 80 % primarily because of the ideal nuclear features of ^{99m}Technetium, vast availability of radionuclide generator system and also the emergence of new labelling techniques (International Atomic Energy Agency (IAEA), 2008).

2.3 SPECT-CT

Over the past years, SPECT has been used widely for qualitative and quantitative assessment of radiopharmaceuticals distribution in vivo. The SPECT acquired images usually used for oncological applications. Besides that, physiological information based on localisation of radiopharmaceuticals in the regions of interest can be obtained through SPECT. However, inaccuracy has been one of the major limitations in the analysis of SPECT imaging. The inaccuracy is often resulting from incorrect compensation for attenuated photons. This situation may cause the reconstructed image shows an apparent decline in activity which eventually reaches a minimum at the centre of the image despite of uniform source distribution (Patton J.A. and Turkington T.G., 2008). Therefore, recently a system comprising of SPECT and x-ray CT has been developed to cater this problem. This combined system is expected to provide a more accurate understanding of the both the anatomical and functional aspect of the diseased organs and also for the quantification of SPECT images through non-uniform attenuation correction (Kashiwagi.T *et al.*, 2002).

A high-output x-ray tube and an arc of detectors in a fixed geometry are required to obtain CT images. The rapid rotation of the x-ray tube and also the detector enable the acquisition of cross sectional transmission images. Thus, high quality and spatial resolution images of cross-sectional anatomy can be obtained through CT imaging (Patton J.A and Turkington T.G., 2008).

The integrated SPECT-CT scanners enable the correlation of functional imaging with anatomical structures for the visualisation of any lesions. The sensitivity and specificity of scintigraphic findings increases with the incorporation of anatomical information. SPECT-CT also offers the opportunity to add true diagnostic information derived from CT imaging (Buck *et al.*, 2008). Recent clinical experiences have proved that SPECT-CT imaging manage to provide the interpreting physician with a higher level of confidence in providing diagnostic information. In addition, the availability of anatomic data from CT in fused images adds diagnostic information in almost 30 % of the cases and also higher contributions in specific disease processes (Patton J.A. and Turkington T.G., 2008).

2.3.1 Collimator

Collimator in SPECT imaging plays a vital role in the control of extrinsic imaging characteristic which include noise, resolution and sensitivity of the final functional image. All photons that are not included within a small angular range are normally rejected by the collimators. Thus, collimators are known to low geometric efficiencies. Geometric efficiencies refer to the percentage of detected emitted photons. The maximum energy of photons that can be handled by collimator indicates the energy rating of a collimator. The energy range that designed for specifically for low energy collimators is from 140 to 200 keV. As for medium energy collimators, the designated energy range is 300 to 400 keV. Furthermore, septal thickness reflects the energy rating of collimators (Williams S., 2002).

There are three types of collimators which are parallel hole, converging and diverging and pinhole. Parallel collimators usually provide a constant field of view. Objects placed against the collimator with decreased distance from the camera face provide the best image resolution. Converging collimators are used to magnify an image while diverging collimators are used to minify an image. Pinhole collimators are also used to produce magnified images (Williams S., 2002).

2.4 Environmental condition of SPECT-CT examination room

Environmental conditions like temperature, humidity and background radiation must be regulated and maintained within the acceptable range. This is because high temperature and humidity can lead to expensive failures. When the temperature is decreased by air conditioning, the humidity of the area will increase rapidly. The increase in the humidity could result in the quest for a dehumidifier. Besides that, the room temperature also should not be allowed to undergo any rapid change and not more than 5°C/h in order to avoid any crystal fracture (International Atomic Energy Agency (IAEA), 2009). Furthermore, since photomultiplier tube (PMT) is susceptible to temperature and humidity, any changes in both the parameters could cause changes in PMT properties (Madsen M.T., 2015). In addition, it is very crucial to monitor the background radiation of the surrounding to detect if there any leakage of radioactive materials (International Atomic Energy Agency (IAEA), 2009).

2.5 Thermoluminescence Dosimeter (TLD)

Thermally stimulated luminescence, more commonly known as thermoluminescence (TL) refers to the light emitted in the heating of a solid sample which could be either insulator or semiconductor that was previously excited by radiation. Generally, TL materials tend to absorb energy upon the exposure to any form of radiation either ionising, visible light, or UV and the energy is stored until heated. Thermoluminescence glow curve demonstrates the intensity of emitted light as a function of temperature or time. The function of various energy traps is indicated by the glow peaks (Furetta and Weng, 1998).

The basic principle relies of thermoluminescence is based on the electron band theory. The electron bands are valence and conduction bands. Pairs of charger carriers, electron and holes are formed upon the exposure of TL materials to ionising radiation. Electrons will be released from valence band to the conduction band. The release electron will cause a hole in the valence band. The charger carriers will move freely within the conduction and valence band until these charger carriers be trapped in traps with a certain probability based on the amount of energy to the crystals to produce electrons in shallow traps or deep traps. Traps refer to energy states within the energy band which is usually being produced by impurities. When the crystals are heated until their energy is increase, the crystals will leave the traps and recombine at luminescence centres. This eventually leads to light emission (Ogundare *et al.*, 2006).

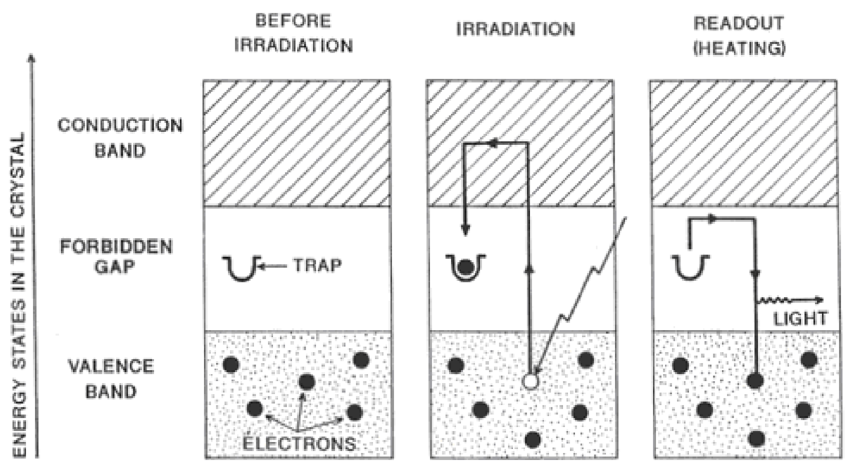

Figure 2.2 The schematic diagram of luminescence excitation and emission in TL materials.

TL detectors are materials that can emit light where the light intensity when heated post radiation exposure, is proportional to the dose of irradiation. The materials used as TL detectors can be either natural or synthetic. In reality, TL materials are phosphors with accumulation. These phosphors have active centres which are relatively stable at ambient temperatures. In recent times, there are a lot of TL phosphors that are being used for various dosimetry applications. Lithium fluoride, calcium fluoride, lithium borate and calcium sulphates are among the most frequently used TL phosphors. There phosphors are manufactured in variety of forms which include chips, pellets, small rods or powder which is encapsulated for irradiation (Ranogajec-Komor, 2003).

Thermoluminescence dosimeters (TLDs) are widely used for radiation detection in various fields especially environmental, industrial, medical and personnel applications. Besides that, TLDs are also commonly used for the measurement of the absorbed dose. Different radiation qualities over a wide range of absorbed dose can be determined using TLD because of the different physical form of the variety of material used in TLD (Bello A.A., 2008).

The application of TL dosimeters in medical field was developed due to their size which small enough to facilitate point measurements, integrative dose recording, tissue equivalence, high sensitivity and also ability to perform multiple measurement at the same time. Since TLD is insensitive to most of environmental agents like temperature and humidity, it can be applied for wide variety forms of radiation and their evaluation can be automated easily. TLD is a very promising dosimetric tool for medical purposes due to the technical advances in the production of TLD materials and also the availability of reading devices (Kron T., 1999).

2.6 Radiation Absorbed Dose

In various nuclear medicine procedures, radionuclides are often given to patients for diagnostic and therapeutic applications. Therefore, the absorbed dose to different organs of the patients is given critical attention (Stabin *et al.,* 1999). Radiation absorbed dose refers to the amount of energy absorbed per unit mass at a given point. The radiation dose is usually calculated as mean absorbed dose of specific organ of interest. This indicates that the dose calculated represent the average of the whole organs not any specific point on the organ (Roberston J.S., 1982).

However, in 1979, the International Commission on Radiological Protection (ICRP) has introduced a new dosimetry quantity known as effective dose equivalent. The effective dose represent the equivalent dose which if the dose is received by our whole body in uniform manner, this would lead to same total risk as that actually incurred by a given actual non-uniform irradiation. Since the main aim of nuclear medicine is to administer compounds that specifically concentrate in particular organ of interest for either diagnostic or therapeutic purposes, thus, the 'whole body' doses are not required. Effective dose enable direct comparison of variety of radiopharmaceuticals which have different radiation dose patterns (Stabin M.G., 2008).

2.7 Anthropomorphic Phantom

Anthropomorphic phantoms are models of human anatomy that are invented primarily for the purpose of radiation dose distribution in calculation in human body once exposed to radiation sources. Phantoms can be classified into two classes depending on the manner to represent human anatomy which include stylised and also tomographic phantoms. Stylised phantom refers to phantom that uses simple mathematical equations of analytical geometry to describe human anatomy. A large number of voxels represents the assigned tissue type and organ identity is used to represent human anatomy in tomographic phantoms. Tomographic phantoms designed based upon tomographic images that are obtained through medical imaging techniques such as magnetic resonance imaging and computed tomography of real human subjects (Lee C.S. and Lee J.K., 2006).

The underlying reasons that result in the innovation of phantom are from the uniform agreement that the assessment of dose quantity for the purpose of protection should be done in receptor conditions and also the availability of digital computers. Mathematical phantom and also computational approaches like Monte Carlo technique play a vital role in the determination of the location and also size of maximum dose in the body. Anthropomorphic phantoms were invented mainly for the purpose of nuclear medicine rather than radiation protection. In the current years, phantom has been more extensively used to evaluate organ dose in nuclear medicine images, internal and external radiations exposure and also in radiography (Lee C.S. and Lee J.K., 2006).

2.7.1 Torso Phantom

Torso phantom is generally made of a large body-shaped cylinder with lung, liver and spine inserts. Torso phantom tends to stimulate anatomical structures of radioactivity distributions for the upper torso of average to large male or female patients. Torso phantom is often used for the evaluation of non-uniform attenuation and scatter compensation methods as well as in research (BIODEX, 2015).

Figure 2.3 Torso phantom

CHAPTER 3

MATERIALS AND METHOD

3.1 Radiation dose Measurement of ^{99m}Technetium in SPECT-CT imaging

This study was conducted at the Nuclear Medicine Unit, Clinical Trial Centre (CTC), Advance Medical and Dental Institute (AMDI). This unit primarily performs SPECT/CT imaging for diagnostic purposes. The most commonly used radionuclides include ^{99m}Technetium, ^{131}Iodine, ^{57}Cobalt, Gallium and ^{201}Thallium.

3.1.1 Materials

Discovery NM/CT 670 with the Low Energy High Resolution (LEHR) Collimators was the model of hybrid SPECT-CT machine used in this study. BIODEX Anthropomorphic SPECT Torso Phantom was the phantom model used in this study. The dimensions of the phantom are 26 x 38 cm and 24 x 36 cm while the wall thickness is 9.5 mm. The background volume of the phantom is 10.3 L while the volume of liver is 1.2 L.

The radiation dose measurement was performed using Thermoluminescence Dosimeter (TLD). The TLD used in this study was Thermo Scientific TLD-100 where Lithium Fluoride (Li natural), LiF:Mg,Ti used as the detector material. The size of the TLD chip is 3.2 × 3.2 × 0.89 mm. Meanwhile, the measurement range of the TLD is from 10 pGy to 10 Gy. Since the TLD used is Thermo Scientific TLD-100, the compactable TLD reader model that was used is Thermo Scientific HARSHAW TLD Model 3500 Manual Reader with WinREMS software.

In addition, 451P Pressurised μR Ion Chamber Radiation Survey Meter was used to monitor the background radiation. Apart from that, Atomlab 500 PLUS was the dose calibrator preferred. Atomlab 500 PLUS consists of Atomlab 500 Dose Calibrator and Atomlab Wipe Test Counter. Terra's EnviroWatch hygrometer was used to measure the temperature and humidity at the SPECT/CT examination room.

3.2 Methodology

3.2.1 Physical Inspection of SPECT-CT Examination Room

Before the phantom scanning was performed, physical inspection was carried out at SPECT-CT examination room. This is to ensure that the environments in the rooms are within the safe level. The physical parameters that were inspected include the background radiation level throughout the examination room. The background radiation level inspection was performed using 451P Pressurised μR Ion Chamber Radiation Survey Meter. The temperature and humidity were also recorded using Terra's EnviroWatch hygrometer. The SPECT-CT imaging can only be conducted if all the three physical parameters are within the safe working limit. Once the physical inspection has been completed, the dose calibrator was calibrated. The dose calibrator that was used is Atomlab 500 PLUS. The dose calibrator consists of two counters which are well counter and wipe test counter. The well counter has high activity since it is used to measure the activity of the radionuclides. While, the wipe test counter has low activity and very sensitive so it is used to test if there is any contamination. Constancy and accuracy tests will be conducted daily and the results must be recorded for reference.

3.2.2 TLD annealing and calibration

Prior to radiation exposure, the TLDs must undergo annealing process. The annealing procedure was done using Nabertherm Furnace where its maximum heating rate is 15 °C/min. 10 TLDs chips were place on a metal plate and annealed at 400 ^{o}C for a period of 1 hour. Once the high temperature annealing procedure has completed, the TLDs were allowed to cool down at 100 ^{o}C for 2 hours. Then, the TLDs chips were stored at room temperature. Besides that, the TLDs must also be calibrated before irradiation. The calibration was done using a fixed dose and read out under same condition. The dose used for calibration was 1.85 mGy over a distance of 1 m.

3.2.3 TLD Sensitivity test

The sensitivity of all the TLDs was evaluated before being used to read doses from the source. The sensitivity test were done by exposing all the TLDs chips to a certain amount of dose and the average reading of all the TLDs were calculated. The TLD chips were annealed at 400 ^{o}C, readout for background reading, and irradiated with a test dose of 1.91 mGy. The read out of the TLDs were done in one session in order to obtain the TL response. The sensitivity factor, S_i was calculated using the following equation (Equation1).

$$\mathbf{S}_{\boldsymbol{i}} = \frac{\dot{\mathbf{M}}}{\mathbf{M}_{\boldsymbol{i}} - \mathbf{M}_{\boldsymbol{0i}}} \qquad \textbf{(Eq: 1)}$$

Where,

$\dot{M}$ is the average net reading in the batch

$M_i - M_{0i}$ is the net TL response corrected for background

3.2.4 Preparation SPECT-CT machine prior to the Imaging

Once the physical inspection and calibration has completed, the SPECT-CT machine preparation was done. There are several quality controls which include energy peaking, flood uniformity test and Center of Rotation (COR) test (as attached in the Appendices A, B and C) must be done on daily basis prior to the usage of the machine. The SPECT machine was checked first. The condition of SPECT was checked thoroughly to ensure that the machine is in good condition. There are several lights on the surface of SPECT machine and if those lights are stable, this indicates that the machine is in good condition and ready to be used. As for the CT machine, it must undergo tube warm up and also fast calibration. Once the CT has passed both the procedures, it is ready to be used.

Then, ^{99m}Technetium was eluted and injected into the phantom. The liver region of the torso phantom was chosen as the subject of investigation. Approximately 2 mCi of ^{99m}Technetium with concentration 0.0017 mCi/ml was injected into the liver region and 8 mCi ^{99m}Technetium with concentration 0.0008 mCi/ml was injected into the background of the phantom. Society of Nuclear Medicine has specified that the activity of ^{99m}Technetium administered for adult liver should be between 1 to 3 mCi (Royal *et al.*, 2003). The activity of ^{99m}Technetium was calculated using the formula stated below (Equation 2). Next, the TLDs were embedded on the surface of the phantom. A total of 3 TLDs were used each in each scanning. One dosimeter was placed on the right end, while another dosimeter was placed on the left end and the third dosimeter on the centre of the phantom. The phantom has successfully prepped and ready to be scanned.

Formula to calculate activity of ^{99m}Tc at any point in time is:

$A = A_0 e^{-\lambda t}$ **(Eq: 2)**

where,

A_o= Initial Activity of the radioactive material

e = Base of the natural logarithm

λ = Decay constant ($ln_2/T½$)

t = Time (in hours) since the initial activity was measured

3.2.5 SPECT-CT Imaging

The phantom was placed on the couch. Low Energy High Resolution (LEHR) collimators were used for this study since the main aim of SPECT-CT imaging is to produce high quality image using low dose of radiation. LEHR is parallel hole collimator. LEHR have numerous amounts of small and deep holes. The sensitivity of LEHR is approximately 185,000 cpm for 1 uCi source, and the resolution is higher with 0.65 cm at 10 cm from the patient side of the collimator. Next, the CT protocol was set for adult body soft tissue, abdomen imaging. The CT protocol specifications were as in Table 3.1.

Table 3.1 Specification of CT protocol for SPECT-CT imaging

Group Parameters	
Scan type	Helical
Voltage	120 kV
Min Current	80 mA
Max Current	220 mA
Noise Index	14
Slice thickness	3.75 mm
SFOV	Large
CTDI	12.2312 mGy